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RECURRENCE PLOTS AND THEIR APPLICATION TO LONG-TERM HEART RATE RECORDINGS FOR THE ANALYSIS OF CIRCADIAN RHYTHMICITY

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To accurately simulate an individual's sleep-wake cycle on the basis of biomathematical models, it is necessary to record physiological measures in order to determine model parameters as well as changes in the circadian and ultradian cycle of sleepiness [1].

A reliable assessment of *circadian rhythmicity* requires a data collection ranging over at least two circadian cycles, i. e. more than 48 hours of recording should be intended. Adequate measures are core body temperature (CBT) [2] or melatonin secretion [3]; however, these techniques are uncomfortable (rectal CBT), intrusive (plasma melatonin) or extensive (melatonin analysis), especially under long-term conditions and for field recordings.

The ECG, on the other hand, which merely requires the application of electrodes to the skin and the wearing of a mobile recording device, provides a more convenient measurement. It is well known that several time- and frequency domain features of the *heart rate* (HR) time series show indications of circadian rhythmicity [4, 5]. Due to a complex regulation by the autonomic nervous system and the suprachiasmatic nucleus, the HR series is a highly variable and irregular signal. This work investigates if methods of *nonlinear signal analysis* can reveal circadian characteristics of long-term HR recordings.

We report on three young adults who participated in an unsupervised 50-hour data collection protocol during their normal daily routine. A two-channel-ECG was recorded (sample rate: 256 Hz); R-peaks were automatically detected, and heart rate time series were constructed. During recordings the subjects were logging their *subjectively rated sleepiness* every 15 minutes on a visual-analogue scale (VAS) using a PDA. Also, *motoric activity* was recorded (sample rate: 16 Hz) by wrist actometry. Figure 1 provides an overview on the collected data.

The state space trajectories of HR series were reconstructed by time delay embedding (dimension $m = 3$, time delay $\tau = 1$). *Recurrence plots* (RP) provide a 2-dimensional representation of all times when a trajectory revisits approximately the same area in state space [6]. The interpretation of large- and small-scale patterns within a RP reveals different qualities – such as determinism, periodicity, chaos or intermittency – about the trajectory's time evolution. A sliding window (width: 60 minutes) was moved over all HR series; for each window, RPs were constructed.

For all subjects, the occurrence of similar events during the recordings – like peaks and troughs of sleepiness, peaks of physical activity, transitions from sleep to wake or vice versa – resulted in a display of similar patterns in the corresponding RPs. Figures 2 to 5 show respective comparisons of recurrence plots, calculated over HR series during similar events (i. e. *classes*).

While the visual resemblance of recurrence plots over similar events is striking, it proved difficult to distinguish between those classes on the basis of quantitative recurrence-plot features [7]. Furthermore, it is obvious that motoric activity clearly affects the heart rate signal. For future recordings and analyses it'll therefore be desireable to either control for physical activation or to eliminate the influence of motoric activity from the signal.

The presented findings show the potential for developing a method to identify states within a long-term heart rate recording which are modulated by the circadian rhythm.

Index Terms— heart rate variability, subjective sleepiness, motoric activity, circadian rhythm, state space, recurrence plots

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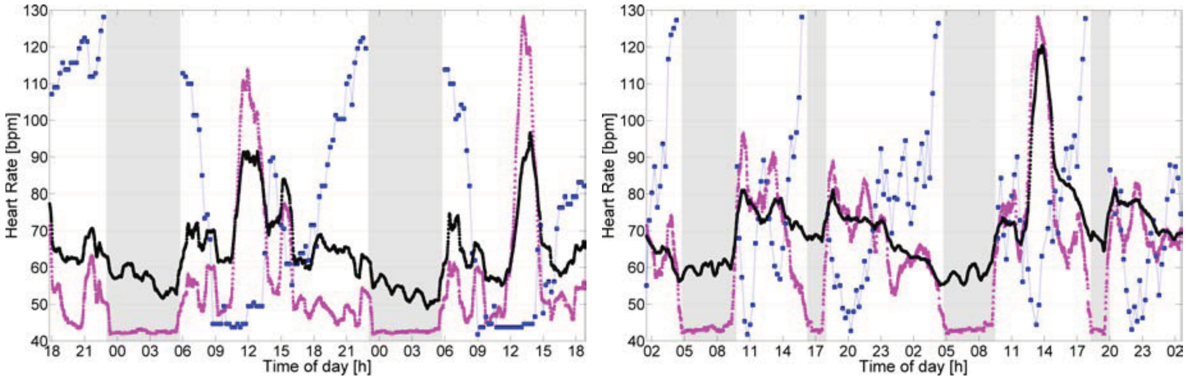

Fig. 1. Comparison of two different recordings: averaged heart rate (●), subjective sleepiness (■) and motoric activity (▲) over 50 hours of data collections for two different subjects, respectively. Sleep episodes are marked as gray bars. Note how subjective sleepiness increases prior to and decreases after sleep episodes. During waking hours, there's an individual trough and peak of sleepiness. Motoric activity is minimal during sleep and shows several individual maxima during waking. Heart rate clearly correlates with motoric activity; it displays deceleration prior to sleep onset, cyclic behaviour during sleep and accerleration after wake-up.

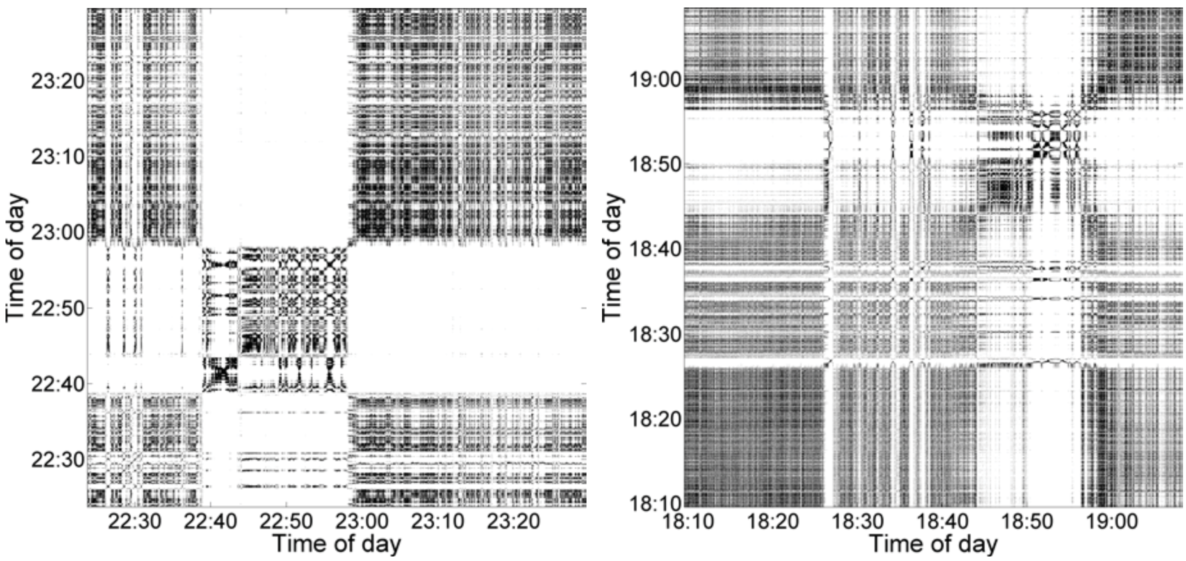

Fig. 2. Recurrence plots ($m = 3$, $\tau = 1$, $\varepsilon = 0.09$) of state-space embedded HR series, each recorded from a different subject. During the displayed course of time, each subject was falling asleep.

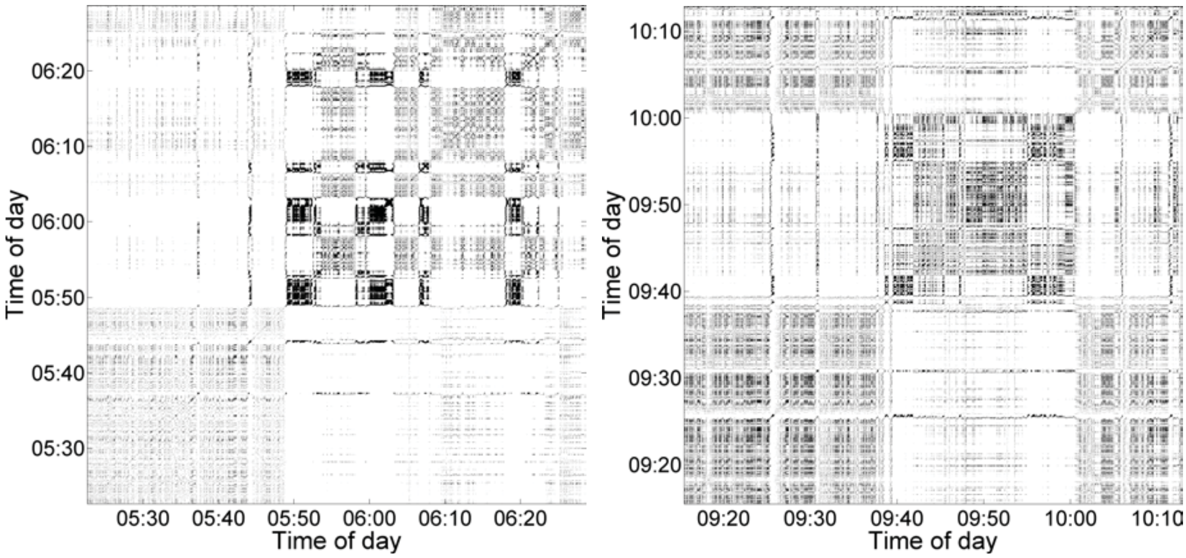

Fig. 3. Recurrence plots ($m = 3,\ \tau = 1,\ \varepsilon = 0.09$) of state-space embedded HR series, each recorded from a different subject. During the displayed course of time, each subject was waking up.

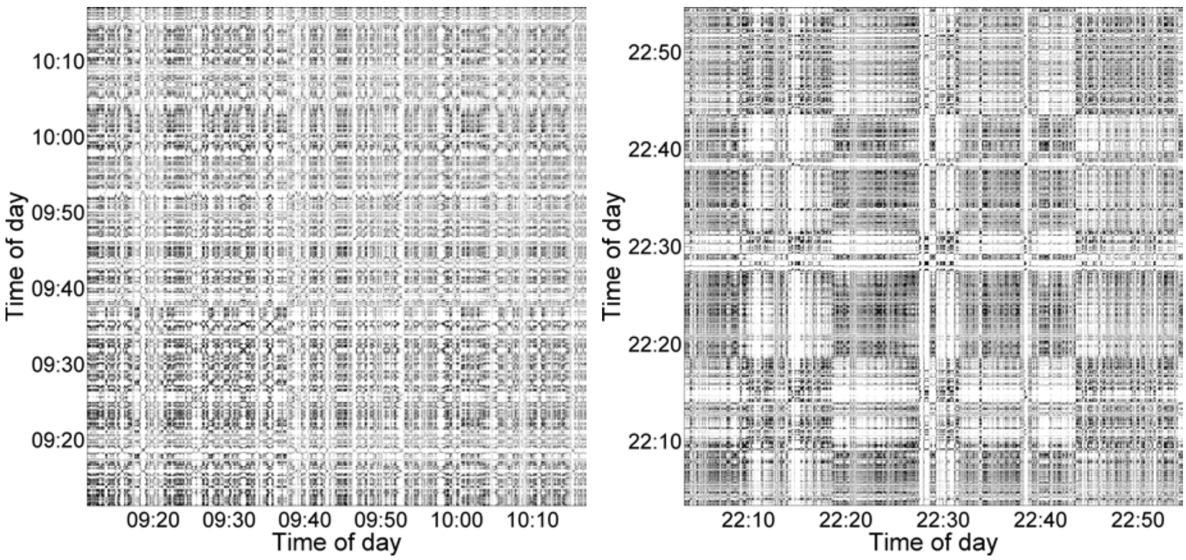

Fig. 4. Recurrence plots ($m = 3,\ \tau = 1,\ \varepsilon = 0.09$) of state-space embedded HR series, each recorded from a different subject. During the displayed course of time, the subjects rated themselves as minimally sleepy.

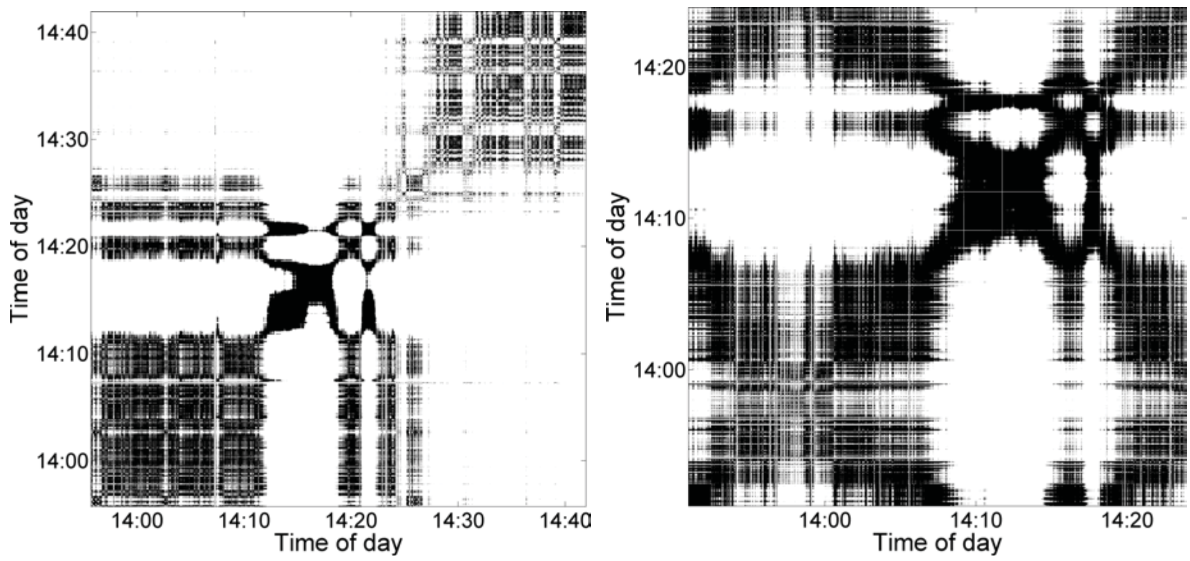

Fig. 5. Recurrence plots ($m = 3$, $\tau = 1$, $\varepsilon = 0.09$) of state-space embedded HR series, each recorded from a different subject. During the displayed course of time, a maximum of motoric activity was recorded for each subject.

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